Refactoring the Curiosity Rover's Sample Handling Architecture on Mars

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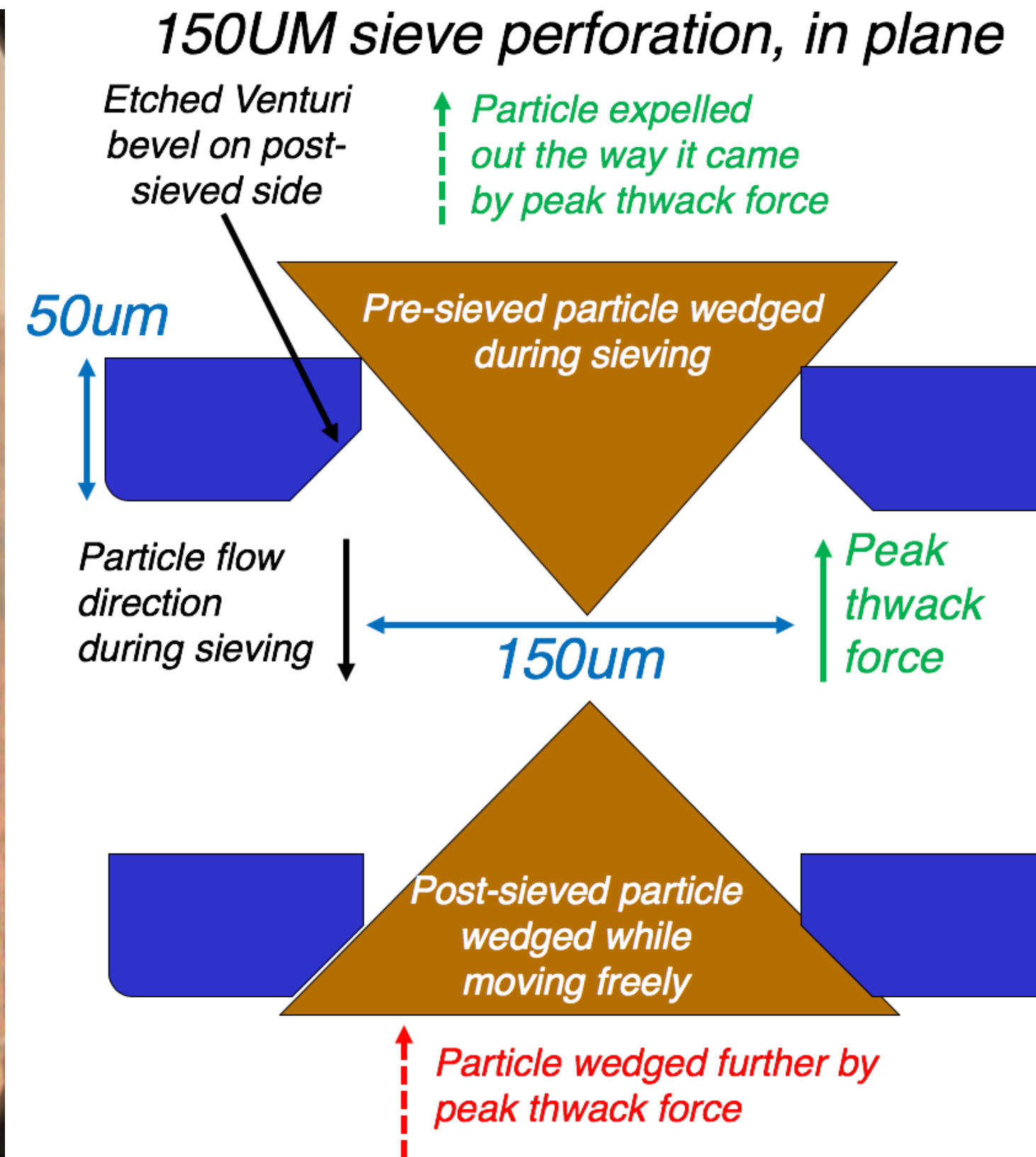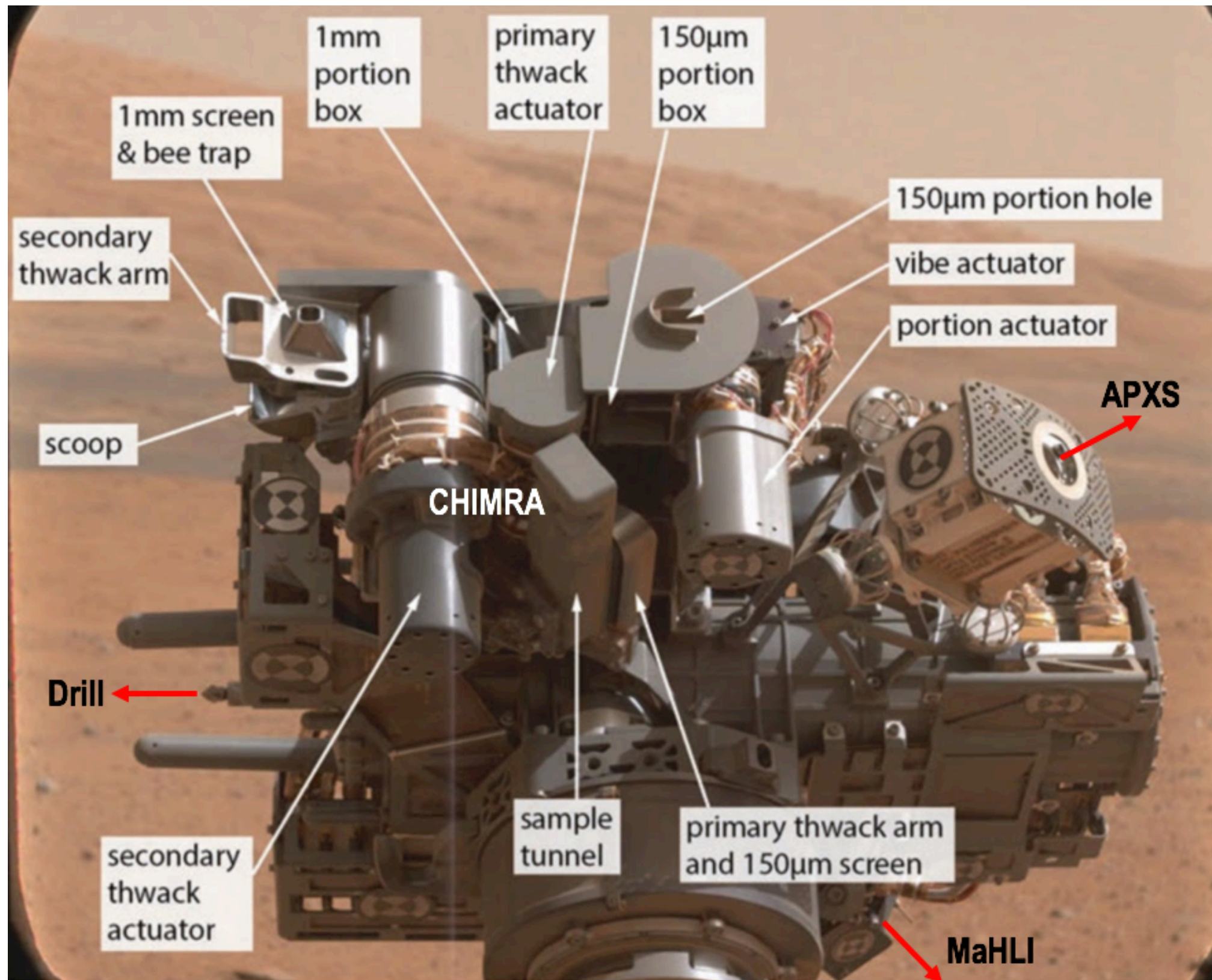## (abstracting the shared development effort of many)
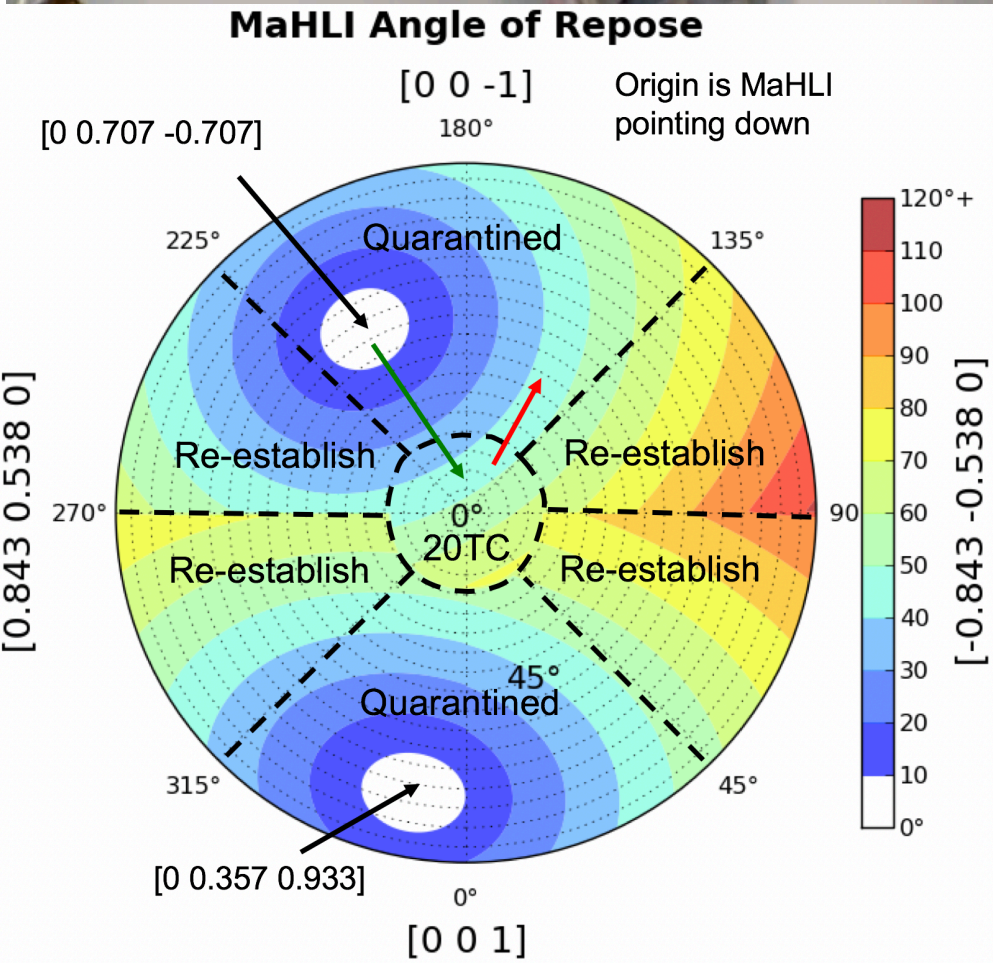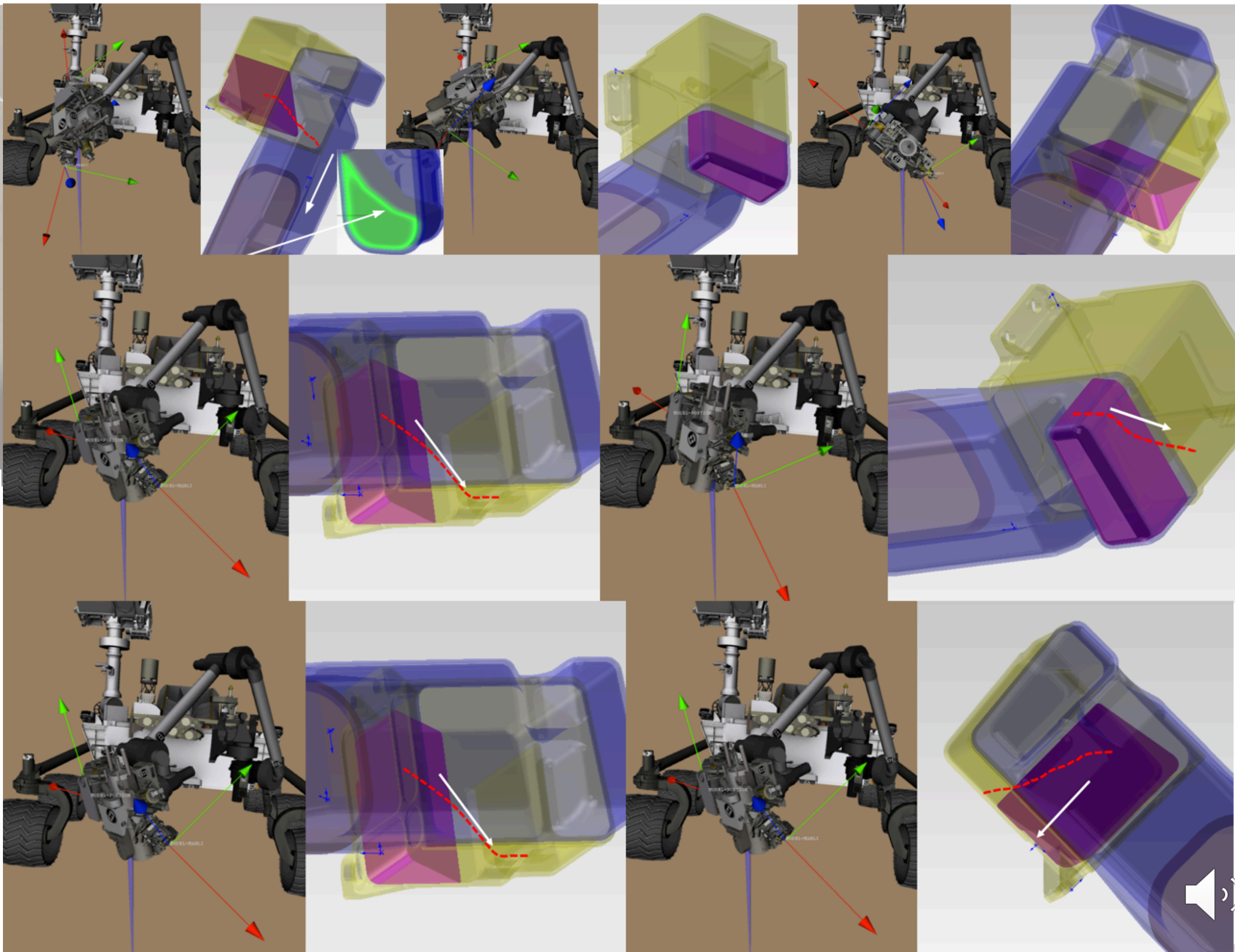
Introduction

- **The Mars Science Laboratory ("MSL") hardware was architected to enable a fixed progression of activities that essentially enforced a campaign structure.**

  - **In this structure, sample processing and analysis conflicted with any other usage of the robotic arm.**

    - **Unable to stow the arm and drive away**
    - **Unable to deploy arm instruments for in-situ engineering or science**
    - **Unable to deploy arm instruments or mechanisms on new targets**

- **Sampling engineers developed and evolved a refactoring of this architecture in order to have it both ways**

  - **Turn the hardware into a series of caches and catchments that could service all arm orientations.**

  - **Enable execution of other arm activities with one "active" sample preserved such that additional portions could be delivered.**

The Foundational Risk

Labels on the rover photo (left):
- 1mm screen & bee trap
- 1mm portion box
- primary thwack actuator
- 150μm portion box
- secondary thwack arm
- 150μm portion hole
- vibe actuator
- portion actuator
- scoop
- APXS
- CHIMRA
- Drill
- sample tunnel
- primary thwack arm and 150μm screen
- secondary thwack actuator
- MaHLI

Diagram (right):

150UM sieve perforation, in plane

Etched Venturi bevel on post-sieved side

Particle expelled out the way it came by peak thwack force

50um

Pre-sieved particle wedged during sieving

Particle flow direction during sieving

Peak thwack force

150um

Post-sieved particle wedged while moving freely

Particle wedged further by peak thwack force

The Original Approach

MaHLI Angle of Repose

Underpinnings of the original approach

- **Fundamentally, human rover planners simply could not keep track of sample in CHIMRA as it sluiced, stick-slipped, fell over partitions, pooled in catchments, etc.**
  - **Neither could we update the Flight Software to model this directly.**

- **But, with some simplifying abstraction of sample state and preparation of it into confined regimes of orientation, ground tools could effectively track sample.**
  - **Rover planners' use of Software Simulator was extended to enforce a chain of custody in commanded orientation, creating a faulted breakpoint upon violation that could be used to fix it.**
  - **Macros help people mold their regular tasks to this architecture with commands that better preserve orientation.**

The Evolution of the Approach

- **With time, the approach evolved.**
- **Serendipity**
  - **Activities undertaken in connection with another anomaly helped us to evolve the caching of sample to a point where it could be sequenced indistinguishably from times when no sample was present.**
  - **Using the original approach for as long as we did gave a wealth of data that became statistically credible in its own right.**
- **Shock-and-awe**
  - **If the risk is existential, assault it on all sides**
    - **Technical – it shouldn't happen from first principles**
    - **Observational – we'll be able to catch it before it's fatal**
    - **Situational – in real, non-simulated conditions, we haven't seen it.**

The Technical

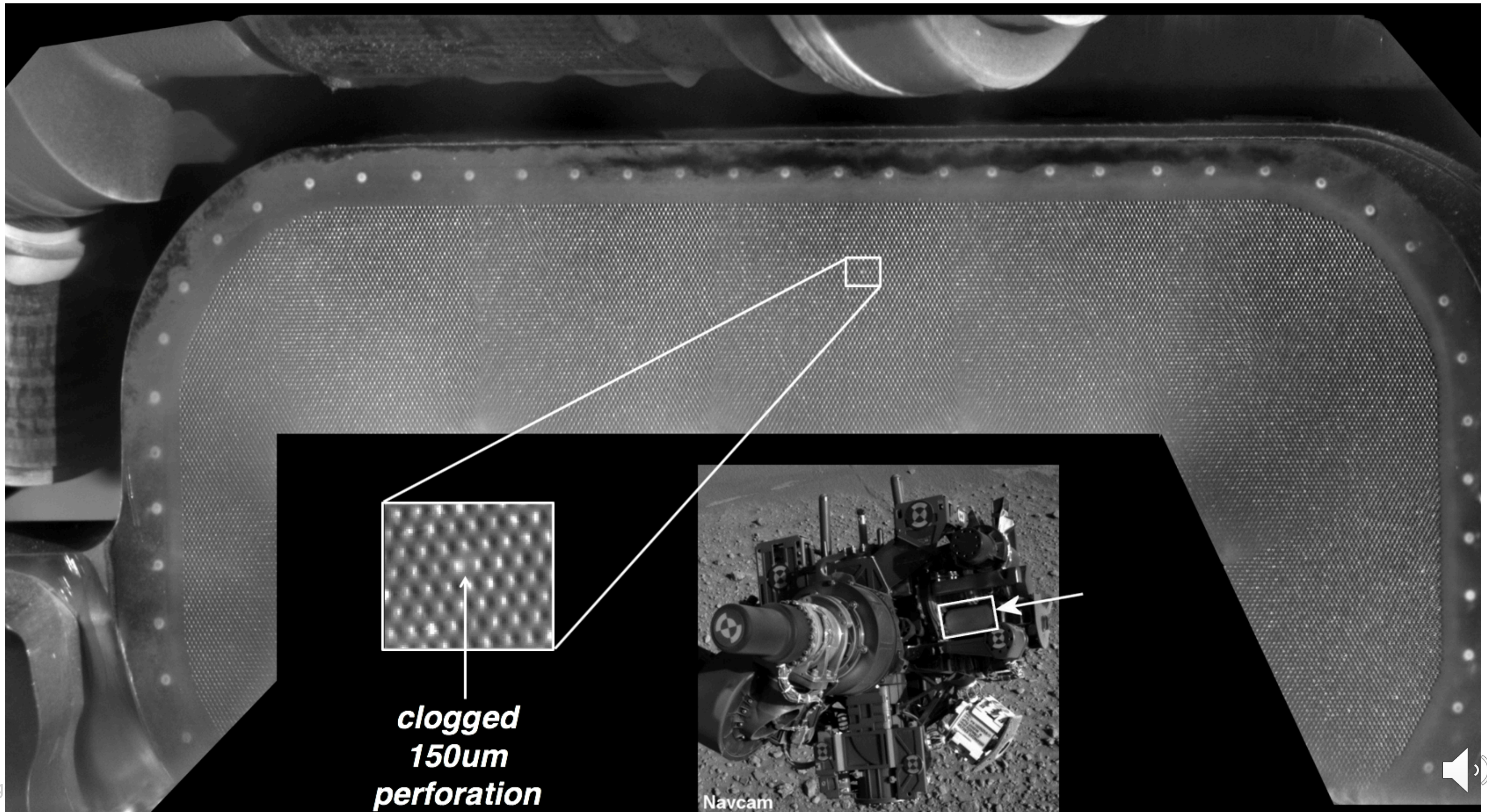MSL QM CHIMRA
Primary Twacker
QMDT Sieve, Run 01
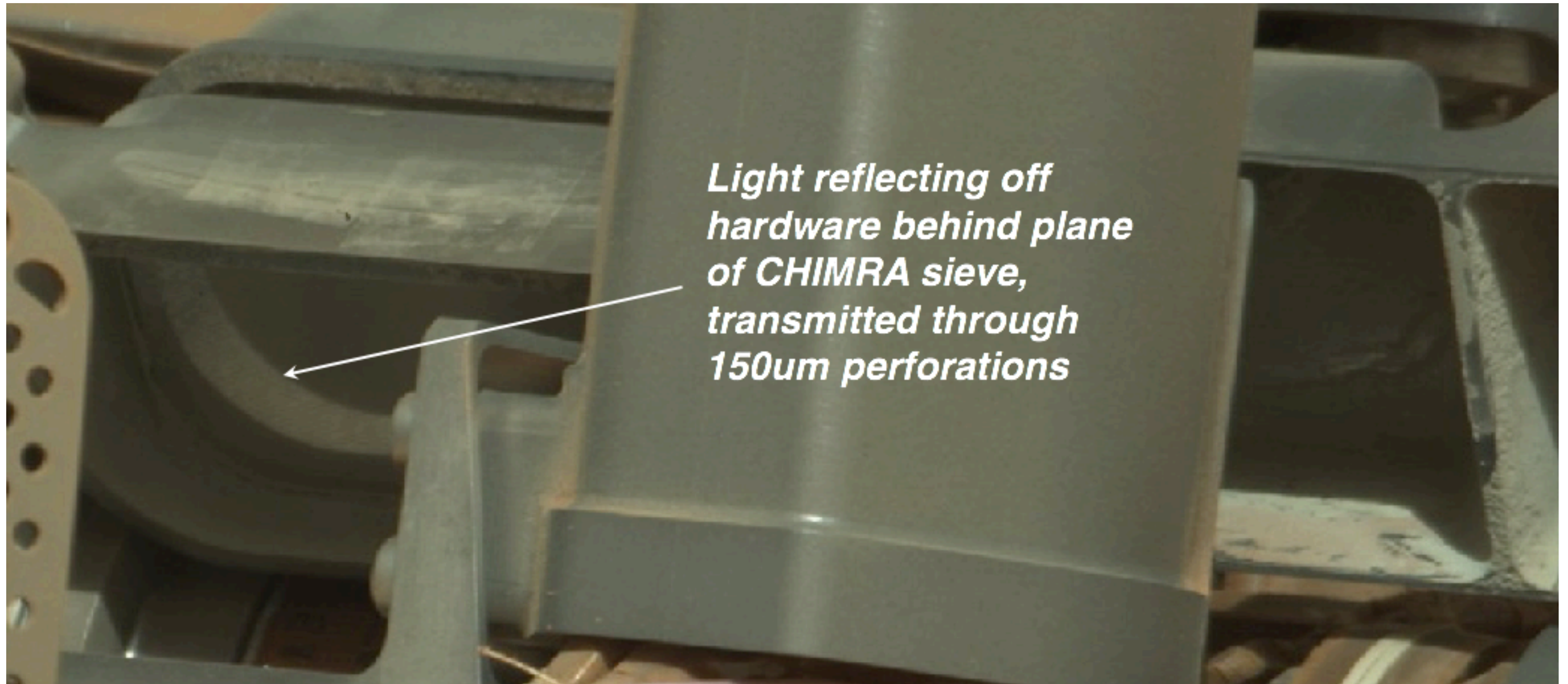Camera A:
Capture: 5,000 fps
Replay: 10 fps
06 December/2012

The Observational

clogged
150um
perforation

Navcam

The Observational

Light reflecting off hardware behind plane of CHIMRA sieve, transmitted through 150um perforations

The Situational

- **The original approach to cached sample definitely exposed constrained portions of the reverse side of the sieve to sample.**

  - **This was part of the original design – limit the sieve area so exposed**

- **With diagnostic imaging, we could resolve that these portions of the sieve were un-degraded.**

- **While this was inadequate on its own, the difference in behavior of drilled samples on Mars compared to terrestrial atmospheric test chambers provided support for the use of flight data to further ease our projected risk.**

Advantages

- **The capability itself enabled scientists to avoid difficult decisions about blocking progress to puzzle over results.**

  - **One of the most exciting samples – Cumberland – was kept in CHIMRA for nearly eight months.**

  - **Through Sol 1540 when the drill feed mechanism failed, about half of all mission contact science was performed with sample still "latent" inside CHIMRA, ready to be dumped later.**

- **The way the approach was implemented supported flexibility and quick turnaround as the capability evolved.**

Disadvantages

- **For a long time, caching sample resulted in greater command overhead to perform the same functions.**
  - Specific usage metrics indicated about 40% more motion commands were required than when sample wasn't cached.
- **As with any new capability, it came with a development cost.**

Lessons/Conclusions

- **The ability to implement complex autonomous constraint checking in ground tools that could be quickly developed and deployed was vital to enabling this repurposing of the hardware for more and better science.**

- **Future missions of a nature that operations might evolve significantly with time, degradation of hardware, or for other reasons, may wish to provision the means to an unanticipated end, rather than condescending to maturity from the outset.**

Authors Biography

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- Vandi Verma is a Robotics Technologist and Supervisor of the Operable Robotics group in the Mobility and Robotic Systems Section at NASA JPL.

- She designed and developed MSL's Software Simulator ("SSIM"); has been a rover planner on MER and MSL since 2008; helped develop MSL's sample processing and AEGIS autonomous flight software; and is working on Robotic Arm and Sample Caching algorithms for Mars 2020.

- She has a Ph.D. in Robotics from Carnegie Mellon University. Her thesis was on particle filters for robot fault detection and identification.

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- Stephen Kuhn has been the flight systems engineer for the CHIMRA mechanism on the Mars Science Laboratory mission; a rover driver on MSL; the On-Board Planner flight systems engineer for Mars 2020; and held other systems engineering roles on MSL and the Mars 2020 missions at JPL.

- He received a B.S. in Mechanical Engineering from Carnegie Mellon University in 2008 and an M.S. in Aerospace Engineering from the Massachusetts Institute of Technology in 2010.